Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering
13 (4) (2021) 0005~0018

Research article

Investigation and optimization of the effect of input parameters on output parameters of electrical discharge machining of A356 nano-composite reinforced by SiC

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(Manuscript Received --- 29 Jan. 2022; Revised --- 06 Mar. 2022; Accepted --- 09 Mar. 2022)

Abstract

In this study, the impact of input parameters of Electrical Discharge Machining (EDM) on A356 nano-composite reinforced by 6% SiC was investigated and optimized using Taguchi's method based on the L9 orthogonal array and dummy level approach. We considered voltage, current intensity, pulse on-time, and pulse off-time as the input parameters. Furthermore, material removal rate (MRR), tool wear rate (TWR), and surface roughness (SR) were taken into account as the output parameters. The analysis of results and examination of the signal-to-noise graphs (S/N) and analysis of variance (ANOVA) were performed using Minitab@16 software. Moreover, with the determination of the loss function of total normalized values of the output parameters based on assumed weight coefficients, the optimal level of each input parameter was established. Besides, the magnitude of contribution percentage of each of the input parameters in the total variance was computed through the variance analysis. According to the achieved results, the second level of the voltage (250 V), the first level of the current intensity (10 A), the third level of the pulse on-time (100 µs), and the first level of the pulse off-time (30 µs) were determined as the optimal input parameters. The contribution percentage of the input parameters for voltage, current intensity, pulse on-time, and pulse off-time was determined respectively to be 20.7, 62.06, 9.19, and 8.05.

Keywords: Electrical Discharge Machining (EDM), Nano-composite, Taguchi method, Variance analysis, Optimization.

1- Introduction

A remarkable rise in the need for engineering machining of metals and alloys with high strength and high resistance against heat has resulted in great advances. Electrical Discharge Machining (EDM) is a great example that has found many applications, especially for pieces with high hardness. The EDM process for the first time was employed by two Russian scientists in 1943 by the invention of the relaxation circuit through the manufacturing of a simple milling machine [1, 2]. Performed studies in EDM have chiefly focused on the change and control of optimum settings of machining parameters of workpiece material. The use of statistical methods, optimization, and especially the design of experiments has mainly been the main focus of the investigations. The elementary study of the EDM process was carried out by Erden and Bilgin in 1980 [3]. They investigated the effects of mixture powder on the dielectric of EDM and suggested that the material removal rate (MRR) increases with the increase of powder concentration. Afterward, Ming and He [4] studied the effect of adding different materials to dielectric liquid during EDM of high-carbon steel on MRR and surface roughness (SR). This research indicated that additives not only improve the quality of the surface but also can increase MRR and decrease tool wear rate (TWR). Mohan et al. [5] utilized EDM with hollow tubular electrodes to perforate silicon carbide composite 6025. According to their studies, circular electrodes increase MRR. Furthermore, they found that general EDM with tubular electrodes results in a higher MRR and a lower TWR and SR of the workpiece. George [6] studied EDM of carbonic composite materials using the Taguchi approach. They concluded that if input parameters are adjusted based on their minimum values, TWR will diminish substantially, and if they are adjusted based on their maximum values, MRR will increase considerably. Kansal et al. [7] examined the impact of dielectric fluid powder on steel alloy of AISI 52100. They proposed that the higher the concentration of the silicon powder, the higher the MRR, and the more the surface roughness. Abedpour et al. [8] specified the effect of EDM parameters on the surface of CK45 steel workpiece. They evaluated the surface roughness and concentration of surface microcracks after each change in EDM parameters. They found that pulse on-time and current intensity play a major role in surface quality.

Kuppan et al. [9] studied EDM of Inconel 718 with the rotary tool. Their research results indicated that the tool rotation increases MRR significantly. Rajmohan and Prubho [10] optimized MRR during EDM of stainless steel 304 by using Taguchi's experiment design. To do this optimization, they considered voltage, current intensity, pulse on-time, and pulse off-time as input parameters. Their research results demonstrated that current intensity and pulse off-time have the largest impact on the MRR of the stainless steel 304. They also indicated that despite the small number of experiments in the L9 orthogonal array of the Taguchi method, appreciable results will achieve by using this approach. Through the central combined experiment method and by conducting 30 experiments, Gopakalannan et al. [11] investigated the effect of each of the input parameters of EDM on MRR, TWR, and SR of 7075 aluminum alloy. In this research, it was found that current intensity and pulse on-time had the greatest impact on outputs such that with the increase of current intensity, MRR would initially increase and then decrease. Moreover, with the increase of current intensity and pulse on-time, the quality of the surface would enhance. Sidhu et al. [12] investigated the effect of additive materials of graphite and copper powder on EDM of three different types of metal matrix composite. They reported that the high conductivity of suspended copper particles leads to the enlargement of sparks and the reduction of the insulating power of dielectric for plasma channel between electrodes. Sadr et al. [13] investigated the effect of input parameters and determined their optimum levels in the EDM process on DIN 1.2080 alloy using two approaches of Taguchi's experiment design and optimum determinant. They showed that the higher current intensity and pulse on-time and the lower voltage and pulse on-time result in the higher MRR and the lower SR. They also proposed a neural network model for the prediction of the material removal rate and determined the optimum value of the removal rate using a genetic algorithm and validated it by experimental observations [14]. Fattahi and Pak [15] investigated the effects of adding different nano-powders to the dielectric. They also examined the simultaneous application of ultrasonic oscillations during EDM of H13 steel. They observed that the simultaneous use of nano-powder particles and the application of ultrasonic waves enhanced the MRR averagely by 30%. Lotfi and Daneshmand [16] investigated the effect of current intensity, voltage, pulse on-time, pulse off-time, and titanium oxide nano-particles on MRR, TWR, and SR of aluminum composite material reinforced by titanium oxide nano-particles during EDM. The results suggested that TWR and SR will increase with the increase of current intensity and pulse on-time, and TWR will diminish with the increase of pulse off-time. Dastjerdi et al. [17] examined the effect of alumina powder on output parameters of EDM of A413 aluminum composite reinforced by alumina. They concluded that the presence of powder in dielectric gives rise to a reduction in MRR, TWR, and SR of the workpiece.

The A356 nano-composite reinforced by SiC is utilized in various and sensitive industries because of its lightness, high strength, and high hardness. Despite the increasing application of composite materials and especially nano-composites, no previous research has been performed to improve machining conditions during EDM of this nano-composite. Since only a few researchers have employed the Taguchi method for experiment design and optimization, statistical analysis and optimization of EDM of this nano-composite material were considered as objectives of this study. With considering the research results and with the application of statistical tools, the effect of process parameters and the importance of each of them are determined and compared. The input parameters of the experiments consist of voltage, current intensity, pulse on-time, and pulse off-time. Moreover, the output parameters consist of MRR, TWR, and SR of the workpiece. To examine the impact of each of the input parameters on the output parameters, the signal-to-noise graphs (S/N) for each of the outputs parameters vs. variations of the input parameters are obtained using Minitab@16 software. The analysis of variance (ANOVA) was also performed using the above-mentioned software. Given the loss function of total normalized values of the output parameters based on assumed weight functions, the optimal level corresponding to each of the input parameters is determined. Finally, with analyzing variance, the contribution percentage of each of the input parameters during the design of experiments is identified according to the corresponding total loss function.

2- Material and methods

For conducting the experiments, the primary workpiece was prepared from the A356 nano-composite reinforced by 6% SiC. The constitutive elements of A356 alloy along with their weight percentages are shown in Table 1. Note that the initial workpiece used in this study was produced by using a resistance melting furnace in which the temperature and velocity of mixer rotation were controllable. For making the sample, A356 alloy was first put inside a graphite crucible. Then it was heated via a resistance furnace up to the melting temperature. After the complete melting of alloy, by inserting the graphite mixer into the melted material, the mixing process was performed while 6% SiC was added to the melted material. Ultimately, the melted material was subjected to casting when it was placed inside a metallic mold with a rectangular cube shape.

Table 1: Constitutive elements of A356 alloy along with their weight percentages [18]

Al	Si	Mn	Mg	Zn	Fe
93.275	6.104	0.013	0.425	0.063	0.18
Ti	Ni	P	Pb	Ca	
0.009	0.006	0.002	0.002	0.005	

For easy measurement of the mass of the workpiece before and after each experiment (i.e. machining), the primary workpiece was cut into nine cubic pieces (in line with nine designed experiments) by using wire cut. The dimension of each piece was selected to be 1×2×2 cm and each piece was numbered by a mandrel (Fig. 1).

Fig. 1 Cubical workpieces prepared for experiments of EDM

The electrodes made from pure copper (99.9%) with a density of 8.94 gr/cm^3, a diameter of 8.4 mm, a height of 4 cm, and a positive polarity were employed in this study. Equal to the number of prepared workpieces, electrodes with the same conditions and scale were prepared and each electrode was assigned to a workpiece (Fig. 2). Note that the used dielectric was a mixture of gasoline and kerosene with equal percentages (i.e., half gasoline and half kerosene).

Fig. 2 Copper electrodes used in EDM of pieces

The utilized apparatus was Tehran-Ekram electrical discharge machine (model 204H). First, the workpiece and the electrodes of each experiment were placed on the electrical discharge machine. Then based on the table of experiments design, the input parameters for each piece were adjusted on the machine. Finally, the electrical machining was performed on each workpiece (according to Fig. 3). The EDM conducted on each workpiece consisted of ten minutes of perforation on the workpiece.

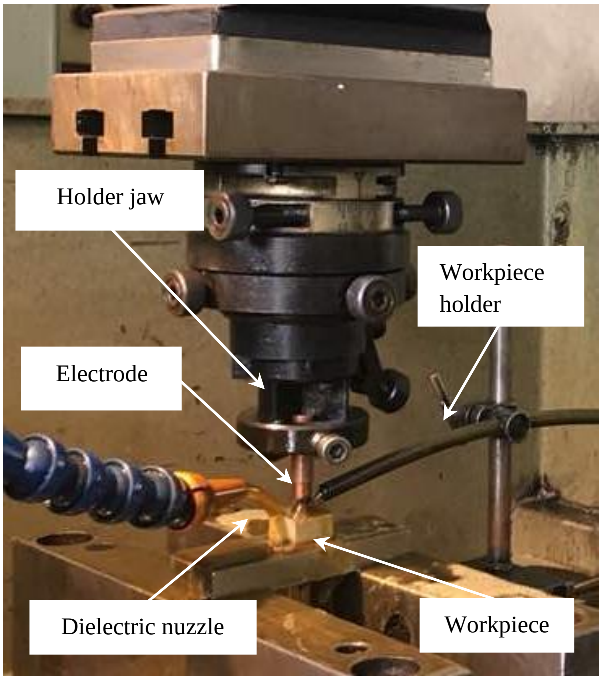

Fig. 3 Schematic of EDM process conducted in this study

After conducting the experiment and machining, the quality of the surface of all workpieces was evaluated by a roughness meter apparatus (Mahr M300-RD18 model). It should be noted that the required surface for measuring the SR is equal to the base surface of a cylindrical hole made on the workpiece with a diameter equal to the tool's diameter (i.e., 8.4 mm). For determining the MRR and TWR, the mass of all composite pieces and that of all electrodes before and after machining were measured by the Sartorius scale (Quintix model) with a 0.001 gr accuracy.

3- Experiments design

We investigated the impact of four input parameters (i.e., voltage, current intensity, pulse on-time, and pulse off-time) on three output parameters (i.e., MRR, TWR, and SR) during EDM of A356 nano-composite reinforced by 6% SiC. The type and number of the levels of input parameters are identified based on attainable settings of the apparatus and according to conducting a series of primary experiments. These are carried out to investigate the intensity of the effect of various levels of the input parameters on outputs of the machining. After determining the parameters and their levels, the procedure of performing the experiments has to be determined. Considering the number of parameters and selected levels and thus, the significant cost and time of conducting all experiments, the Taguchi method was employed in this research [19]. To minimize the number of experiments, the L9 orthogonal array (including nine experiments) and duplicated levels technique (with the repetition of the voltage level of 80) were utilized. This was because the used spark apparatus had only two voltage levels, unlike other input parameters that had three levels. The repetition of the first level for the third level of voltage was performed because of the more significant effect of this level of voltage on machining outputs during the initial experiments. Table 2 exhibits the machining input parameters and their levels. Table 3 also shows the pattern of conducting the experiments on workpieces.

Table 2: Machining input parameters and their selected levels

Level	Voltage (V)	Current intensity (A)	Pulse on-time (μs)	Pulse off-time (μs)
1	80	10	35	30
2	250	15	50	70
3	80	20	100	200

Table 3: Pattern of conducting the experiments based on Taguchi design approach

Experiment No.	Voltage (V)	Current intensity (A)	Pulse on-time (μs)	Pulse off-time (μs)
1	80	10	35	30
2	80	15	50	70
3	80	20	100	200
4	250	10	50	200
5	250	15	100	30
6	250	20	35	70
7	80	10	100	70
8	80	15	35	200
9	80	20	50	30

4- Determination of the output parameters

After adjusting the input parameters (i.e., voltage, current intensity, pulse on-time, and pulse off-time) for each experiment and machining of the pieces of A356 nano-composite reinforced by 6% SiC, we calculated MRR, TWR, and SR. The values of MRR and TWR were calculated via Eqs. 1-2 as follows [19]:

$$MRR = \frac{(W_1 - W_2)}{\rho_w \times t} \times 10^3 \quad (1)$$

$$TWR = \frac{(T_1 - T_2)}{\rho_T \times t} \times 10^3 \quad (2)$$

where W_1 and W_2 are respectively the workpiece mass before and after the machining; T_1 and T_2 are respectively the tool mass before and after the machining; ρ_w and ρ_T are the density of the workpiece and density of the tool, respectively, and t is machining time in minutes. The obtained results for the outputs during the nine designed experiments are displayed in Table 4.

Table 4: The output parameters of EDM of A356 nano-composite pieces reinforced by 6% SiC

Experiment No. (Piece No.)	SR (μm)	MRR (mm^3/min)	TWR (mm^3/min)
1	4.130	15.483	0.056
2	7.493	26.903	0.191
3	6.482	29.319	0.169
4	4.555	15.922	0.079
5	5.999	16.508	0.011
6	5.047	25.476	0.146
7	5.728	23.133	0.022
8	3.619	7.321	0.067
9	6.323	27.745	0.213

5- Signal-to-noise ratio (S/N) of the outputs

After analyzing the signal-to-noise ratio of outputs obtained by Minitab@16 software, we scrutinized and analyzed the effect of input parameters of EDM of A356 nano-composite reinforced by 6% SiC on output parameters, separately. Note that for MRR, an increase (a decrease) of signal-to-noise ratio (S/N) indicates an increase (a decrease) of MRR, and for TWR and SR of the workpiece, an increase (a decrease) of S/N shows a decrease (an increase) of TWR and SR.

5-1- MRR results

After analyzing the S/N of MRR of A356 nano-composite reinforced by 6% SiC, the obtained results are reported in Fig. 4. We observe that with the increase of voltage, MRR lessens slightly. With increasing voltage, because of reinforcement of the electrical field in the plasma channel, positive ions hit the workpiece surface more strongly. However, the accumulation of melted swarfs on the workpiece surface prevents the average rise of MRR. With the increase of current intensity from level 1 to level 2, although the volume of positive ions hitting the workpiece surface increases, the intensity of ions contact with the surface reduces because of the increase in swarfs accumulation in the machining area. Therefore, MRR averagely decreases during the EDM. With further increase of current intensity from level 2 to level 3, the effect of bombardment volume rise of workpiece surface by ions dominates the effect of the swarfs accumulation in the machining area. Thus, MRR will enhance with a drastic slope. Furthermore, it is observed that with the increase of pulse on-time from level 1 to level 2, because of the rise in time of electrical current connection and appropriate time for further enlargement of the plasma channel (and thus, more invasion of positive ions towards workpiece), MRR increases. Then with a change of level from 2 to 3, due to more accumulation of workpiece swarfs within the machining area, the energy density in the electrical discharge area diminishes. This causes the MRR slope to slightly become negative because of the increasing pulse on-time. Moreover, with the increase of pulse off-time from level 1 to level 2, because of enough opportunity for cooling of swarfs and faster exit of them from the machining area (for prevention of swarfs accumulation), MRR increases. Then with the increase of pulse off-time to level 3, the negative slope increases further due to the decrease in volume of invasion of positive ions towards the workpiece.

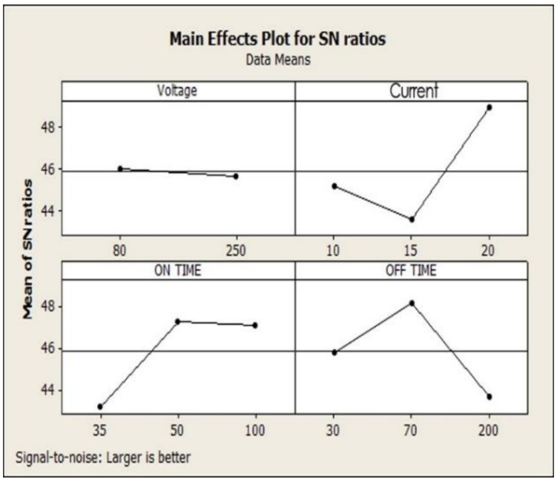

Fig. 4 Diagrams of S/N of MRR based on input parameters

5-2- TWR results

Results of S/N of TWR of machining of A356 nano-composite reinforced by 6% SiC are displayed in Fig. 5. This figure reveals that with the increase of voltage in reinforced nano-composite, despite the increase of electrons energy, TWR reduces. Note that in these experiments, electrons of the workpiece invade and hit the tool electrode. Moreover, with the increase of current intensity, TWR raises due to the increase in the number of exited electrons from the workpiece and their contact with the tool. With the increase of pulse on-time from level 1 to level 2, plasma channel diameter has gradually increased and tool electrode has been invaded by more electrons, resulting in more TWR. With the increase of pulse on-time from level 2 to level 3, the intensity of contact of electrons with the tool electrode has decreased because of further accumulation of swarfs in the machining area. Therefore, less energy has been transferred to the tool electrode. Thus, TWR has diminished.

Finally, the pulse off-time diagram suggests that TWR has increased with a relatively gentle slope from level 1 to level 2 and also from level 2 to level 3.

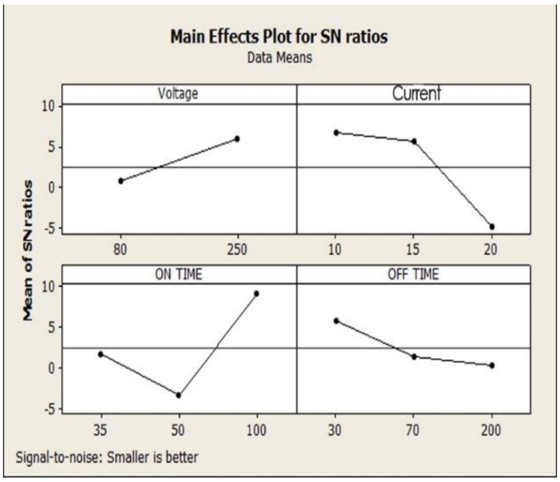

Fig. 5 Diagrams of S/N of TWR based on input parameters

5-3- SR results

Fig. 6 depicts results of S/N of SR of the workpiece after machining of A356 nano-composite reinforced by 6% SiC. With increasing voltage, despite the increase of positive ions energy hitting the surface of the workpiece and the expectation of having deeper valleys, SR has reduced. Furthermore, with the increasing current intensity, SR has increased. This is because the number of positive ions has increased and thus, the intensity of bombardment of workpiece surface by ions has raised, creating more valleys/voids on the surface. The pulse on-time diagram shows that with the increase of pulse on-time from level 1 to level 2, and then from level 2 to level 3, the plasma channel has been reinforced and the intensity of bombardment by ions has increased, causing SR to increase with a sharp slope. The increase of pulse off-time from level 1 to level 2 has increased SR. Then with the increase from level 2 to level 3, workpiece surface quality has improved because of the existence of enough opportunity for washing of the machining area by dielectric as well as regular movement (no interference and energy rise) of positive ions towards the workpiece surface.

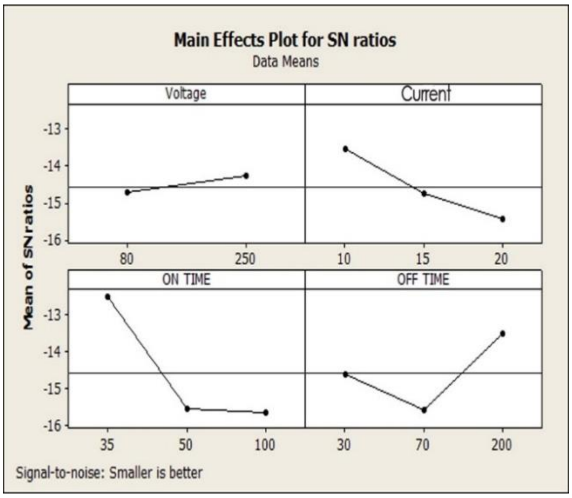

Fig. 6 Diagrams of S/N of SR based on input parameters

6- Optimization of the process

To determine optimum values of EDM parameters, the method of multiple signal-to-noise ratio (MSNR) was used [20, 21]. In this technique, the loss function of each of the outputs has to be computed for every experiment. For each of the experiments, the loss function of MRR (L_{MRR}) should be calculated using Eq. 3 because the larger calculated MRR is better.

$$L_{MRR_i} = 1/MRR_i^{\,2} \qquad i = 1,2,3,\dots,9 \tag{3}$$

If the output of the experiment is SR or TWR, because the smaller calculated SR or TWR is better, Eqs. 4-5 are utilized respectively to calculate the loss function of SR (L_{SR}) and the loss function of TWR (L_{TWR}).

$$L_{SR_i} = SR_i^{\,2} \qquad i = 1,2,3,\dots,9 \tag{4}$$

$$L_{TWR_i} = {TWR_i}^2 \quad i = 1,2,3,\ldots,9 \tag{5}$$

Considering the assumed importance for each output in this research, the weight coefficients of 0.5, 0.3, and 0.2 were considered for MRR, SR, and TWR, respectively. For each of the experiments, total normalized quality loss (TNQL) was computed according to Eq. 6 as follows:

$$TNQL_i = 0.5\ \frac{L_{MRR_i}}{L_{MRR_{max}}} + 0.3\ \frac{L_{SR_i}}{L_{SR_{max}}} + 0.2\ \frac{L_{TWR_i}}{L_{TWR_{max}}} \quad i = 1,2,3,\ldots,9 \tag{6}$$

To normalize the data, the S/N of each output has been divided to the corresponding maximum value of experiments. Given calculated TNQL, the value of S/N of all outputs (MSNR) is calculated for each experiment via Eq. 7 as follows:

$$MSNR_i = -10\log(TNQL_i) \quad i = 1,2,3,\ldots,9 \tag{7}$$

Then the average value of S/N of all outputs corresponding to each of the input parameters is computed by considering the selected level and table of experiments design (Eqs. 8-19). The input parameters in this procedure consist of voltage ($\mathrm{MSNR_{voltage}}$), current intensity ($MSNR_{current}$), pulse on-time ($MSNR_{on\ time}$), and pulse off-time ($MSNR_{off\ time}$).

$$MSNR_{voltage_1} = (MSNR_1 + MSNR_2 + MSNR_3)/3 \tag{8}$$

$$MSNR_{voltage_2} = (MSNR_4 + MSNR_5 + MSNR_6)/3 \tag{9}$$

$$MSNR_{voltage_3} = (MSNR_7 + MSNR_8 + MSNR_9)/3 \tag{10}$$

$$MSNR_{current_1} = (MSNR_1 + MSNR_4 + MSNR_7)/3 \tag{11}$$

$$MSNR_{current_2} = (MSNR_2 + MSNR_5 + MSNR_8)/3 \tag{12}$$

$$MSNR_{current_3} = (MSNR_3 + MSNR_6 + MSNR_9)/3 \tag{13}$$

$$MSNR_{on\ time_1} = (MSNR_1 + MSNR_6 + MSNR_8)/3 \tag{14}$$

$$MSNR_{on\ time_2} = (MSNR_2 + MSNR_4 + MSNR_9)/3 \tag{15}$$

$$MSNR_{on\ time_3} = (MSNR_3 + MSNR_5 + MSNR_7)/3 \tag{16}$$

$$MSNR_{off\ time_1} = (MSNR_1 + MSNR_5 + MSNR_9)/3 \tag{17}$$

$$MSNR_{off\ time_2} = (MSNR_2 + MSNR_6 + MSNR_7)/3 \tag{18}$$

$$MSNR_{off\ time_3} = (MSNR_3 + MSNR_4 + MSNR_8)/3 \quad (19)$$

Results of the application of the above equations are presented in Table 5. Among selected levels for each input parameter, the level corresponding to the maximum value of MSNR of the same input parameter is considered as the optimal value for that parameter. Thus, the optimum levels of input parameters corresponding to considered TNQL are identified according to Table 5. Therefore, the optimal value of 250 V for voltage, 10 A for current intensity, 100 µs for pulse on-time, and 30 µs for pulse off-time was determined for the machining process with considering defined TNQL.

Table 5: Average of S/N of all outputs corresponding to each parameter in various levels

	Corresponding levels of input parameter		
Input parameter	Level 1	Level 2	Level 3
Voltage (V)	4.6178	5.7159	4.0686
Current intensity (A)	6.3982	3.5603	4.4438
Pulse on-time (µs)	4.8660	4.2122	5.3241
Pulse off-time (µs)	5.1606	5.0411	4.2006

7- Variance analysis

To determine the importance of the effect and relative contribution of input parameters in the design of experiments, the analysis of variance is performed according to the considered total loss function. Sum of squares (SS), degree of freedom (D), Variance (V), and contribution percentage in total variance (P) are four parameters employed frequently in the analysis of variance. These parameters are calculated based on the following procedure [22, 23]. First, the total sum of squares of deviations (SS_T) is computed by using Eq. 20 as follows:

$$SS_T = \sum_{i=1}^{9} (MSNR_i - MSNR_m)^2 \quad (20)$$

where $MSNR_m$ is the average of all S/N of all outputs for nine experiments. That is:

$$MSNR_m = \left(\sum_{i=1}^{9} MSNR_i \right) / 9 \quad (21)$$

Moreover, the sum of squares of deviations corresponding to each of the input parameters is computed via Eqs. 22-25 as follows:

$$SS_{voltage} = \sum_{i=1}^{3} 3\left(MSNR_{voltage_i}\right)^2 - \frac{1}{9}\left(\sum_{i=1}^{9} MSNR_i\right)^2 \quad (22)$$

$$SS_{current} = \sum_{i=1}^{3} 3\left(MSNR_{current_i}\right)^2 - \frac{1}{9}\left(\sum_{i=1}^{9} MSNR_i\right)^2 \quad (23)$$

$$SS_{on\ time} = \sum_{i=1}^{3} 3\left(MSNR_{on\ time_i}\right)^2 - \frac{1}{9}\left(\sum_{i=1}^{9} MSNR_i\right)^2 \quad (24)$$

$$SS_{off\ time} = \sum_{i=1}^{3} 3\left(MSNR_{off\ time_i}\right)^2 - \frac{1}{9}\left(\sum_{i=1}^{9} MSNR_i\right)^2 \quad (25)$$

Furthermore, the variance of each input parameter is calculated by Eqs. 26-29 using the degree of freedom of that parameter as follows:

$$V_{voltage}(\%) = \frac{SS_{voltage}}{D_{voltage}} \times 100 \quad (26)$$

$$V_{current}(\%) = \frac{SS_{current}}{D_{current}} \times 100 \quad (27)$$

$$V_{on\ time}(\%) = \frac{SS_{on\ time}}{D_{on\ time}} \times 100 \quad (28)$$

$$V_{off\ time}(\%) = \frac{SS_{off\ time}}{D_{off\ time}} \times 100 \quad (29)$$

The error of squares sum of deviations (SS_e) is computed by using Eq. 30 as follows:

$$SS_e = SS_T - \left(SS_{voltage} + SS_{current} + SS_{on\ time} + SS_{off\ time}\right) \quad (30)$$

The error variance (V_e) is calculated by Eq. 31 using the degree of freedom of experiments error (D_e) as follows:

$$V_e = \frac{SS_e}{D_e} \quad (31)$$

The modified sum of deviations squares (SS') of each input parameter can be determined by Eqs. 32-35 using the degree of freedom of that parameter.

$$SS'_{voltage} = SS_{voltage} - D_{voltage}V_e \quad (32)$$

$$SS'_{current} = SS_{current} - D_{current}V_e \quad (33)$$

$$SS'_{on\ time} = SS_{on\ time} - D_{on\ time}V_e \quad (34)$$

$$SS'_{off\ time} = SS_{off\ time} - D_{off\ time}V_e \quad (35)$$

The contribution percentage of each of the input parameters in the total variance can be computed using Eqs. 36-39 as follows:

$$P_{voltage}(\%) = \frac{SS'_{voltage}}{SS_T} \times 100 \quad (36)$$

$$P_{current}(\%) = \frac{SS'_{current}}{SS_T} \times 100 \quad (37)$$

$$P_{on\ time}(\%) = \frac{SS'_{on\ time}}{SS_T} \times 100 \quad (38)$$

$$P_{off\ time}(\%) = \frac{SS'_{off\ time}}{SS_T} \times 100 \quad (39)$$

Finally, the contribution percentage of error in the total variance (P_e) is calculated by Eq. 40 as follows:

$$P_e = 100 - \left(P_{voltage}(\%) + P_{current}(\%) + P_{on\ time}(\%) + P_{off\ time}(\%)\right) \quad (40)$$

After performing the variance analysis calculations of the design of the experiments, obtained results are shown in Table 6. Considering the defined total loss function, we observe that the current intensity is the most important parameter in the EDM process because of having the largest contribution percentage of the influence (62.06%). The next effective parameters are voltage, pulse on-time, and pulse off-time with the contribution percentage of 20.7, 9.19, and 8.05, respectively.

Table 6: The variance analysis results of the design of the experiments

Parameter	Degree of freedom (D)	Sum of squares (SS)	Variance (V)	Modified sum of squares (SS')	Contribution (P, %)	Degree of importance
Voltage	2	4.2209	2.1105	4.2209	20.7	2
Current intensity	2	12.6541	6.3271	12.6541	62.06	1
Pulse on-time	2	1.8737	0.9368	1.8737	9.19	3
Pulse off-time	2	1.6423	0.8212	1.6423	8.05	4
Error	0	0	0	0	0	
Sum	8	20.3911			100	

As observed in Table 6, the error percentage is zero. In the analysis of variance, if the error contribution in the total variance is smaller than 15%, this means that all effective input parameters have been considered in the design of experiments [24].

8- Conclusion

In this research, the effect of the input parameters of voltage, current intensity, pulse on-time, and pulse off-time on the output parameters of MRR, TWR, and SR was investigated during EDM of A356 nano-composite reinforced by 6% SiC. In this regard, Taguchi's experiment design method based on the L9 orthogonal array was adopted. Minitab@16 software was utilized to draw and analyze the S/N of the outputs corresponding to each of the input parameters. With the definition of an appropriate loss function from total normalized values of the outputs based on considering desired weight coefficients for each of the output parameters, the optimization stages of S/N of all outputs were carried out. According to the results of optimization performed on the experiments design of EDM, the second level of voltage (250 V), the first level of current intensity (10 A), the third level of pulse on-time (100 μs), and the first level of pulse off-time (30 μs) were identified as the optimum levels of the input parameters. In the end, for determining the relative contribution of the effect of each of the input parameters in the design of the experiments, the required steps for the variance analysis were presented by considering a loss function. The results of the variance analysis indicated that the current intensity was the most important parameter because it had the largest contribution percentage (62.06%).

The next influential parameters were voltage, pulse on-time, and pulse off-time with the contribution percentage 20.7, 9.19, and 8.05, respectively.

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